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Examination of space/volume requirements for US underground coal mine refuge alternatives

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Abstract

The Mine Safety and Health Administration requires that 1.4 m^2 (15 ft^2) of floor space is to be provided for each person inside a refuge alternative (RA). However, the amount of floor space needed for a person to reside inside an RA and perform basic tasks is unknown. During testing, participants entered into an RA or a simulated RA of various space/volume configurations and performed several simulated tasks that are representative of the survivability tasks performed within an RA. The results indicate that the floor space requirements were generally adequate for the tasks studied. Certain tasks such as changing scrubber cartridges, using toilets, and moving about the RA were impacted by the minimum height tested (0.6 m). As such, RAs of this height will require critical design consideration as a whole and the supplies provided for use inside of the RA to ensure the ability to use an RA.

Keywords

Restricted posture; human factors; occupational health & safety; ergonomics; fit

Introduction

Refuge alternatives (RAs) in use in various countries include rigid metal enclosures as well as inflatable structures that provide breathable air, food and water, and sanitary facilities for several days (US regulations require four days). Taking refuge within a rigid or inflatable RA poses a range of challenges, such as prolonged, restricted, awkward, and/or static postures. In some areas, such as the effect of prolonged restricted postures on health and performance, there is limited research with direct relevance to RAs. There is, however, research available on space restrictions that can be extrapolated. Several specific issues that relate to RAs, as defined below, were further explored to better categorise the principles/factors at play with regard to the human factors principle of fit – or in the case of design

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Relevance to Human Factors/Ergonomics Theory

This research addresses the human factors principle of fit – i.e. can a person comfortably fit into the space provided and perform the tasks required while in said space. An experimental approach utilising human participants was undertaken to address this human factors design principle.

Disclosure statement

No potential conflict of interest was reported by the authors.

principles, namely the principle of consistency with use, environment, and performance (Norman 1988). The need to understand these principles/factors will be magnified under extended periods of postural restrictions, and will be critical not only for maintaining a certain level of comfort and performing basic nutrition and hygiene tasks, but also for maintaining musculoskeletal performance necessary for potential escape.

Biomechanical concerns for RAs

For RA occupants, extended periods of static postures, such as sitting or sitting with intermittent crawling or lying down, can be expected to result in significant discomfort and a decrease in physical capabilities following the confinement. In the case of seating, significant research and development activities have been performed to design seating to minimise operator fatigue and discomfort, particularly in office environments. Unfortunately, available research studies did not use long exposure periods. Even field studies that examine fatigue and discomfort across work shifts have subject populations that did not have the movement and postural restrictions found in RAs.

Studies have indicated that postures adopted in restricted vertical space can affect the strength capacity and the biomechanical loading experienced by the body. Gallagher et al. (2001) demonstrated that decreases in vertical space were associated with a linear increase in the moment experienced by the lumbar spine in a cable lifting task. Lifting capacity has been shown to be reduced in kneeling and stooping postures common to low- and mid-seam mines (Ayoub et al. 1985; Gallagher and Hamrick 1992; Gallagher and Unger 1990). The decreased strength capacity and increased biomechanical loading in restricted postures may impact the ability of miners to perform tasks required in emergency situations and increase the risk of injury in low-to-medium-thickness seam operations.

There have been studies to investigate seat design with eight-hour exposures to seating and the resulting discomfort. Pellettiere et al. (2006) reported a study that involved subjects testing four seat cushions, each for an eight-hour exposure. (It should be noted that subjects were required to perform isometric and leg exercises every 30 minutes to reduce the risk of deep vein thrombosis.) Discomfort surveys were completed every two hours, as was a subjective test of physical condition on a scale of 1 (bad), 4 (not well), 7 (ok), to 10 (great). Physical condition ratings decreased from a mean of 9.0–9.5 at the start of the test to below 8.0 after eight hours for males. Female subjects had similar responses, although the female subject group weighing >66 kg (145 lbs) began testing with a mean rating slightly higher than 8.0 and had a mean rating close to 7.5 after testing. Discomfort of the low back and buttocks increased over the test period for both males and females.

Although these findings are subjective, they indicate significant increases in discomfort and decreases in perceived physical condition after eight hours. The subjects were between 21 and 30 years of age and had passed a medical prescreen. It is likely that miners residing in an RA for extended periods, up to 96 hours, will experience significant discomfort and they will have a perceived and likely real decrease in musculoskeletal capability following the confinement.

Anthropometric concerns for RAs

One of the most fundamental ergonomic concerns with RAs is whether or not the volume is sufficient for carrying out required tasks for personal hygiene and activities of daily living (e.g. eating and sleeping), as well as for deploying, entering, and maintaining the RA. Although there is little research on space requirements for RAs, issues such as ingress/egress dimensions for underground equipment have been researched (e.g. Hamrick et al. 1993).

Most anthropometric databases used for ergonomics purposes are either fairly old or are from surveys of military populations. Furthermore, the data were collected from subjects with little or no clothing. Determining space requirements for RAs necessitates considering the following potential issues:

1. The height and width of available space needs to accommodate the majority of miners, which will require using height and width values for 95th percentile males.
2. The space requirements will depend on the anticipated postures of the miners (e.g. seated with legs up and kneeling), the amount of mining equipment worn (e.g. mine belt, hard hat), and tasks that will be carried out at various times (e.g. placing CO_2 scrubber cartridges on top of scrubber housings, monitoring the atmosphere by taking gas readings, etc.).
3. There will need to be sufficient space for miners to reach and use the toilet and adjust the environmental controls.
4. Different vertical heights will require different area configurations to perform required tasks.

MSHA regulations

The Mine Safety and Health Administration (MSHA) requires a minimum of 1.4 m^2 (15 ft^2) of unrestricted floor space per person. MSHA also requires certain unrestricted volumes per person based on coal seam height (Federal Register 2008; http://www.msha.gov/30cfr/7.505.htm). The volume requirements are as low as 0.85 m^3 (30 ft^3) per person for seam heights of 0.9 m (36 in) or less, to 1.7 m^3 (60 ft^3) per person for seam heights greater than 1.4 m (54 in) (see Table 1). The entry airlock – the space provided inside the RA to purge the bad atmosphere before entering the main portion of the RA – can be included in the space and volume calculations, if waste is disposed outside the RA.

Inhabiting RA and tasks required

While inside an RA, miners may be restricted to a height as low as 0.6 m (24 in). The miners must remain in the space until rescuers can reach them, and US requirements are that sufficient supplies are provided for up to 96 hours. Once inside the RA, the miners may choose to remove their mining gear, such as cap lamps, but are not typically instructed to do so by the instructions included with the RA. In the event of a fire or other emergency, the miners may also be using a self-contained self-rescuer rebreather that they will need to discard once inside the RA. While inside the RA, the miners will need to access and use lights, water, food, supplies, environmental controls, and a toilet of some form. The waste from these items will typically need to remain inside the RA. The space each miner is provided inside the RA is at a minimum 1.4 m^2 (15 ft^2), as required by MSHA. Within this space, a miner must be able to reside, store personal supplies, store waste, and perform all required tasks needed for refuge inside the RA.

To better understand the task requirements of residing inside an RA, an informal task analysis was conducted and documentation provided by the RA manufacturers was reviewed. From this work a list of tasks that miners inside the RA must complete was complied. These tasks include the following:

1. Check environmental conditions: The miners are instructed to check up to four gas levels every two hours while in the RA. This is done either by a handheld unit or with a built-in instrument on one of the walls of the RA.

2. Adjust environmental system: If the miners notice any issues during the gas check, they may need to adjust the oxygen (O_2) flow to correct if there is either too much or too little oxygen in the RA. The miners may also need to make adjustments to the cooling system, if provided, by adjusting controls on the system.

3. Maintain CO_2 scrubber: This task varies by RA. In some RAs, five scrubbing cartridges (0.4 m × 0.3 m × 0.15 m (16 in × 12 in × 6 in), 20 kg (44 lbs)) need to be removed from the scrubber housing and replaced every 24 hours. In other RAs, a new curtain or curtains (~1.8 kg (4 lbs) each, one per person) need to be hung inside the RA every 24 hours. The miners are typically not instructed to remove the old curtains.

4. Reach supplies: The supplies (food, water, CO_2 scrubbers) in a rigid-style RA are typically stored under the floor or inside the seats. In a tent-style RA, the supplies are normally stored in the metal box that the tent rolls out from. To access these supplies in a rigid-style RA, workers must move off the access panel (either the seat or a specific floor panel) and raise the access panel to reach the contents. In one model of a rigid RA, the floor access panel was made of steel and weighed 11.3 kg (25 lbs). It measured 0.6 m × 1 m (24 in × 40 in) and the area beneath the floor was 0.1 m (4 in) deep. The water is typically packed in a case (0.4 m × 0.2 m × 0.11 m (15.5 in × 7.75× 4.5 in), 7.3 kg (16 lbs)) and the food in a box (0.33 m × 0.23 m × 0.22 m (12.75 in × 9.125 in × 8.5 in), 14 kg (31 lbs)).

5. Eat food/drink water: The miners are supplied with sealed food and water packages. The water is normally provided in sealed individually packed containers (typically juice box/pouch style) and sometimes provided in five-gallon jugs. The food is normally provided in a food bar format which may need to be broken into smaller pieces and either consumed by one individual over the course of a day or split among several miners. No specific tools are provided to split the food bars.

6. Personal hygiene: The main identified hygiene task is the use of a toilet. Several different models of toilet have been used in the RAs, such as a marine toilet or a folding camping toilet.

7. Repair: Most RAs do not allow for any major repairs to be made while the RA is deployed. Most manufacturers provide instructions and simple tools (i.e. duct tape) for basic RA, scrubber, flash light, and gas meter repair. The steps and tasks to perform these repairs vary between manufacturers.

Experimental research study

There is insufficient evidence to support the idea that 1.4 m^2 (15 ft^2) of floor space per person in an RA is adequate for a person to reside within and perform the required tasks, while taking refuge for a period of up to 96 hours. Additionally, the change in a person's ability to perform a given task and the time it takes to perform the said task in the restricted space of an RA and in different space/volume configurations is not well understood. Research was undertaken to fill this knowledge gap and to better examine the effect that differing space/volume configurations have on a person's ability to take refuge inside an RA and adequately complete required tasks while inside.

Methods

The research study used two laboratory experiments. For both experiments, participants were asked to perform a set of tasks (see later) within a restricted volume. The tasks studied were chosen as a representative sample of those tasks required when taking refuge within an RA as defined by the RA manufacturer and observed during sample deployment of RAs/task analysis. The first laboratory study utilised a commercially available RA, while the second study used several mock-ups with varying space/volume layouts. During each study, the RA/mock-up was filled to capacity (combination of four mannequins, three human participants, and one researcher) as defined by MSHA and manufacturers' guidelines. Once inside, each participant individually performed the required tasks and self-reported their ability to complete the task and their effectiveness and discomfort level while completing the task. The tasks were also timed and observed by the National Institute for Occupational Safety and Health (NIOSH) researcher to determine the success or failure of each task. The order of testing of the nine mock-up conditions (three length/width configurations × three heights) was randomised. The commercially available RA test always occurred last. The order of the task and participant combinations (four tasks per participant × three participants) was fully randomised inside of each condition. At the completion of the tasks inside each RA/mock-up, the participants were asked to rate their opinion of the mock-up/RA condition just completed.

Participants

Fifteen employees (14 males and 1 female) from NIOSH were recruited and participated in this study. The study participants were federal employees located at the Bruceton, PA, research campus. No participant had underground work experience. All participants gave their informed consent to perform after being made aware of the study requirements and potential risks. The participants had a mean age of 30 years (SD ± 6), a mean height of 1.75

m (70 in) (SD ± 0.08 m (3 in)), and a mean weight of 97.5 kg (215 lbs) (SD ± 20.5 kg (45 lbs)). See Table 2 for detail information about each participant's anthropometry. The participants were generally in very good health and physical condition.

Procedures

For each condition, the participants were asked to simulate several basic tasks. The task, description, and failure criteria are listed as follows:

Moving around inside the RA (Move)

- Description: The participants were asked to move from the front to the back (the longest side) of the RA/mock-up. (Note: the distance was held constant for all participants within each RA/mock-up.)
- Failure criteria: Participant unable or unwilling to reach the other side of RA, or stopped by researcher for safety concerns.

Simulated changing of a CO_2 scrubber cartridge (Lift)

- Description: The participants were asked to move from their location at that time to the location of a simulated scrubber cartridge. The participants then moved the simulated cartridge from its storage location to the back of the RA/mock-up. When the participants reached the back of the RA/mock-up, they lifted the cartridge 0.3 m (1 ft) onto a simulated scrubber housing. The participants then returned to their original location. The simulated CO_2 scrubber cartridge weighed 11.3 kg (25 lbs) and was 0.3 (12) long × 0.4 (16) wide × 0.15 (6) high meters (inches), with no handles. The participants were allowed to transport/lift the cartridge by any means they felt appropriate without the assistance of other participants. (Note: 11.3 kg (25 lbs) was chosen for safety concerns with this participant population, while miners in a real mining situation routinely lift 18–27 kg (40–60 lbs) in restricted workspaces.) In their study, Gallagher et al. (1988) found that the 12 miners tested would on average self-select to lift weights up to a maximum of 26.8 kg (59 lbs) while kneeling.
- Failure criteria: Participant unable or unwilling to reach the scrubber cartridge, unable or unwilling to transport cartridge, unable or unwilling to lift cartridge, or unable or unwilling to return to their original location, or stopped by researcher for safety concerns.

Simulated eating and/or drinking (Drink)

- Description: The participants were asked to open and drink from a pre-packaged water container.
- Failure criteria: Participant unable or unwilling to open and drink from the pre-packaged water container, participant spilled all contents of the package (a small amount of spillage was allowed), or stopped by researcher for safety concerns.

Set-up and simulated use of the toilet (Toilet)

- Description: The participants were asked to move from their location at the time to the toilet. The participants then set up the toilet by unlocking and unfolding the legs. The participants then sat on the seat of the toilet and remained there for 10 sec. The participants then returned to their original location. The toilet used for testing in the mock-ups was a portable plastic folding toilet designed for camping or hunting (see Figure 1). The toilet used for testing in the commercially available RA was a ceramic marine toilet.
- Failure criteria: Participant unable or unwilling to reach the toilet, unable or unwilling to sit on the toilet, unable or unwilling to remain on the toilet for 10 sec, or unable or unwilling to return to their original location, or stopped by researcher for safety concerns.

Apparatus

Commercially available RA (Part 1)—The RA used for Part 1 of the study was leased from its manufacturer. The RA has a capacity of eight people and is 5.2 (17) long × 2.4 (8) wide × 1.7 (5.5) high meters (feet) in exterior dimensions (Figure 2). There are two doors to pass through to enter the main living area of the RA – one exterior door and an interior door from the entry area to the main living area. Inside the RA, there are eight seats for the participants to use. MSHA may allow the use of the airlock floor space to be included in the overall floor space calculation; for this reason the interior door of the RA remained open during all testing.

Mock-up RAs (Part 2)—Three mock-ups were used in Part 2 of this study; each mock-up was built to have a maximum capacity of eight people (Figure 3). The interior dimensions (m (ft)) were mock-up A, 3.8 (12.5) long × 2.9 (9.5) wide; mock-up B, 14.9 (16) long × 2.3 (7.5) wide; and mockup C, 6.1 (20) long × 1.8 (6) wide. Each mock-up had a variable height of 0.6, 1.2, and 1.8 m (24, 48, and 72 in). These dimensions were selected to comply with MSHA regulations for 1.4 m^2 (15 ft^2) of floor space per participant while varying the space/volume configurations.

Results

Task completion

The participants were able to complete all tasks for each of the conditions tested (height and mock-up/RA combination, $n = 10$) except for the ‘Set-up and simulated use of the toilet’ at the 0.6 m (24-in) height (see Figure 4). Across all the mock-ups, only four of the 15 participants were able to use the toilet at the 0.6 m (24 in) height. The distribution of completion categories significantly differed across mock-ups A, B, and C ($p < 0.04$ Fisher’s exact test calculated with SAS for Windows 9.3).

Task time

The task of ‘Simulated eating and/or drinking’ was not timed as part of this study. For the ‘Set-up and simulated use of the toilet’ task, only a few individuals were able to complete the task at the 0.6 m (24 in) height. Therefore, the time data for this task and height condition were not analysed due to missing values.

Given the homogenous design of the three mock-ups, repeated-measures analysis of variance (ANOVA) with participants treated as blocks was used to determine if there were significant differences in task completion times due to mock-up design, height, or the interaction between design and height. The RA was a fixed design and not amenable to analysis with the three mock-ups.

For lifting the CO_2 scrubber, both mock-up ($F(2, 111) = 7.50$, $p = 0.0009$) and height ($F(2, 111) = 121.98$, $p < 0.0001$) were significant, whereas the interaction was not ($F(4, 111) = 1.61$, $p = 0.1776$). Times for mock-ups A and B were significantly different from each other as were times for mock-ups A and C, but times for B and C were not significantly different (using Tukey's *post hoc* test). For heights, the mean task times for 0.6 m (24 in) were significantly different from the mean times for 1.2 m (48 in) and 1.8 m (72 in), but the mean times for 1.2 and 1.8 m in times were not significantly different (see Figure 5) (1.8 m (72 in) results are not shown as they mirror the 1.2 m (48 in) results).

For 'Moving around inside the RA' times, both mock-up design ($F(2, 111) = 21.35$, $p < 0.0001$) and height ($F(2, 111) = 77.40$, $p < 0.0001$) were significant, whereas the interaction was not ($F(4, 111) = 1.94$, $p = 0.1088$). The mean movement time for mock-up A (5.1 sec) was significantly lower than the mean times for B (7.1 sec) and C (7.0 sec), but this difference likely does not have practical significance. The mean movement time for the 0.6 m (24 in) height (8.9 sec) was significantly higher than the mean times for the 1.2 m (48 in) (5.5 sec) and 1.8 m (72 in) (4.8 sec) heights.

Since the 0.6 m (24 in) mock-up was missing, most data for completion times of 'Set up and simulated use of the toilet', the ANOVA only included data for the 1.2 m (48 in) and 1.8 m (72 in) heights. Mock-up was not significant ($F(2, 70) = 0.41$, $p = 0.6634$), but height was ($F(1, 70) = 5.72$, $p = 0.0195$). The interaction between mock-up and height was not significant ($F(2, 70) = 0.04$, $p = 0.9604$). The mean task time for mock-up A (43.1 sec) was significantly higher than the mean time for mock-up B (39.0 sec), although the magnitude of time does not likely have much practical significance.

Task effectiveness

For each task that the participants successfully completed, they were asked to self-report their task effectiveness by responding to the following question: 'How effective do you feel you were at performing the task?' on a scale of (1) 'Totally ineffective', (2) 'Ineffective', (3) 'Effective', (4) 'Totally effective' (modified from Vagias [2006]). For both the 1.2 m (48 in) and 1.8 m (72 in) heights for all mock-ups and the commercial RA, the participants all responded with either 'Effective' or 'Totally effective' for all tasks studied (see Figure 6). (The 1.8 m (72 in) height is not shown as it mirrors the 1.2 m (48 in) results.) For the 0.6 m (24 in) mock-up height, the participant responded with either 'Effective' or 'Totally effective' for the 'Simulated eating and/or drinking', the 'Changing of a CO_2 scrubber cartridge', and the 'Moving around inside the RA' tasks. The task effectiveness scores were lower for the small number of participants who were able to complete the 'Set-up and simulated use of the toilet' at the 0.6 m (24 in) height ('Totally ineffective' (*n* = 1), 'Ineffective' (*n* = 3), and 'Effective' (*n* = 3)).

Task discomfort

For each task that the participants successfully completed, they were asked to self-report their task discomfort by responding to the following question: 'During the task, I experienced ______.' on a scale of (1) 'No discomfort', (2) 'Mild discomfort', (3) 'Moderate discomfort', (4) 'Severe discomfort' (modified from Vagias 2006). For both the 1.2 m (48 in) and 1.8 m (72 in) heights for all mock-ups and the commercial RA, the participants all responded with either 'No discomfort' (*n* = 412), 'Mild discomfort' (*n* = 7), or 'Moderate discomfort' (*n* = 1) for all tasks studied (see Figure 7). (The 1.8 m (72 in) height is not shown as it mirrors the 1.2 m (48 in) results.) For the 0.6 m (24 in) mock-up height, the participant responded with either 'No discomfort' (*n* = 43) or 'Mild discomfort' (*n* = 2) for the 'Simulated eating and/or drinking' task. For the 'Changing of a CO_2 scrubber cartridge' and the 'Moving around inside the RA' tasks, the participants all responded with either 'No discomfort' (*n* = 14, 28, respectively), 'Mild discomfort' (*n* = 23, 14, respectively), or 'Moderate discomfort' (*n* = 8, 3, respectively). For the small number of participants who were able to complete the 'Set-up and simulated use of the toilet' at the 0.6 m (24 in) height, the response were 'No discomfort' (*n* = 1), 'Mild discomfort' (*n* = 2), 'Moderate discomfort' (*n* = 3), and 'Severe discomfort' (*n* = 1).

Posture

Figure 8 shows postures used while a participant moving a weighted object from one side of the mock-up to the other side as part of the 'changing of a CO_2 scrubber cartridge' task for each mock-up height. In the three heights studied, the participant was required to adopt different postures to accomplish the required task; this participant posture is representative of all participants performing this task. For the 0.6 m (24 in) height, the participant adopted a crawling posture; for the 1.2 m (48 in) height, a stoop walking posture; and for the 1.8 m (72 in) height, a full upright walking posture. No difference in adopted posture was observed among the three mock-up layouts (mock-up A, B, or C). For the commercially available RA, the participants adopted a posture similar to the 1.2 m (48 in) height stoop walking posture.

Mock-up/RA feedback

At the completion of all tasks in a given condition (height and mock-up/RA combination, *n* = 10), the participants were asked the following general questions: 'I feel I can fit in the space provided to me' (Fit), 'I feel I can remain in the space provided to me for 96 hours' (Remain), and 'I feel I can complete all tasks that may become necessary while in space provided to me for up to 96 hours' (Complete) on a scale of (1) 'Strongly disagree', (2) 'Disagree', (3) 'Agree', (4) 'Strongly Agree' (modified from Vagias 2006). For the 1.2 m (48 in) and 1.8 m (72 in) mock-up heights and the commercial RA, all questions were answered with either 'Agree' or 'Strongly agree' for all participants (see Figure 9). (The 1.8 m (72 in) height is not shown as it mirrors the 1.2 m (48 in) results.) At the 0.6 m (24 in) height, the participants indicated they could fit into the space provided and remain there for the time required, but that they may have difficulty completing tasks at this height required to take refuge (see Figure 9).

Discussion

General conclusions

This was an initial study to examine basic tasks required to survive in an RA given the current space/volume MSHA regulations. Participants overall responded that they thought they could remain in the space and perform the required task to take refuge for 96 hours for RAs with height at or above 1.2 m (48 in).

RA space/volume configuration

No measurable trade-off or preference of how floor space was provided was found amongst the floor layouts examined in the study which varied from almost square to long and thin. Therefore, it is felt that the configuration of floor space is not a significant consideration in the design of RAs for healthy inhabitants performing the simulated tasks studied and in the configurations tested. Participants casually mentioned varying preference for the different mock-up designs, but no consistent pattern was observed. Some participants preferred the square layout as it felt less claustrophobic, while others preferred the long and thin design as it provided each miner an individual section of the RA without having to sit across from another person.

The commercially available RA studied performed comparably to the mock-ups for all measures collected. The entry airlock space for the commercially available RA was included in overall floor space as allowed by MSHA to meet the 1.4-m^2 (15-ft^2) requirement. The result of the entry airlock inclusion as part of the overall floor space was a reduction in the general open portion of the RA. This manufacturer chose to place the toilet in the entry area, thus creating a bathroom area that would allow for privacy. Additionally, while participants verbally indicated they preferred the commercially available RA due to its padded seats, no difference was identified in any discomfort or preference measure collected, indicating that while seats may be more comfortable, they were not required. Within the limitations of this study (see later), 1.4 m^2 (15 ft^2) of floor space per person appears to be sufficient to take refuge other than during the use of the toilet at 0.6 m (24 in), and the participants were able to complete all the tasks studied within a reasonable amount of time with little to no discomfort.

These design aspects, consistency with use, environment, performance, and the overarching human factors principle of fit are critical to the usability of the RA. It is important for refuge manufacturers to consider this information when designing the RA space/volume layout and determining how the space will be provided to each user. Things to consider when designing the space/volume layout would include the intended use of the separate space (i.e. entry airlock, main body) while taking refuge, the location of supplies and controls, and the path which users must traverse to reach supplies or controls.

RA height

Participants overall disliked the 0.6-m (24-in) mock-up height. Many participants felt that while they would be able to fit into the height restriction they would have trouble performing the tasks required of them to take refuge such as repair or personal hygiene-related tasks. In comparison, for heights above 1.2 m (48 in), the participants' opinions of the mock-ups did not vary significantly and were overall very positive. Little to no discomfort was reported and all participants reported being able to complete all required tasks.

It is important for refuge manufacturers to consider this information as well as general anthropometry information, as discussed in the Introduction, when designing RAs. Specifically, RAs with heights of less than 1.2 m (48 in) should be avoided when possible due to participants' inability to use the toilet at 0.6 m (24 in), and the fact that participants reported at 0.6 m (24 in) they could not complete all tasks necessary to remain in the space provided. If an RA with a height of less than 1.2 m (48 in) cannot be avoided, an alternative toilet mechanism should be used which allows a person to fit and comfortably complete required functions, as an 84% failure rate was observed for the toilet design studied.

For the measures studied, no significant advantage was observed for a height above 1.2 m (48 in) for an RA. This may be because the tasks did not require movement of any great distance or strenuous activity. It is possible that a 1.8 m (72 in) height may result in improved performance of tasks not performed in this study, for example, performance of upright lifting may be improved in 1.8 m (72 in) over 1.2 m (48 in) due to increased lifting capacity. Overall, it is important to consider the effect that RA height will have on the users given the information provided when designing an RA, selecting the supplies provided to the users, and the tasks required to successfully operate the equipment.

Limitations

The scope of this research does not address all potential scenarios and tasks involving space/volume configurations of RAs or all tasks required to reside within an RA as described in 'Inhabiting RA and tasks required'. Purging the airlock, assisting injured or unconscious miners, and performing minor repairs are examples of possible tasks required that were not studied. Additionally, the participant population utilised for this study may not be representative of the underground coal mining population and the participants may not have interacted with the mannequins the same way they would have with additional participants. The mock-ups used may not be representative of actual RAs, but the heights studied, particularly 0.6 m (24 in), were based on realistic scenarios. Finally, several of the measures used in this study are based on participants' subjective ratings of the different space/volume configurations after exposure for only a short period of time. It is uncertain how the participants' responses would change after longer duration exposure to the conditions.

Future research

The findings of this research show that configuration of floor space is not a significant consideration in the design of RAs for the range of conditions and tasks studied. However, future research will need to be conducted to determine the trade-off of increasing or decreasing the amount of floor space provided on the requirements of taking refuge in an RA for an extended period of time. Sleeping and injured miners may alter preferences, particularly since preferred postures for both may involve lying down, resulting in different amounts of free floor space. The relationship between height and task performance between the 0.6 m (24 in) and 1.2 m (48 in) heights should be further explored to determine the particular height at which difficulty in completion of the tasks increases. Additionally, alternative means of providing a toilet facility should be explored for use in RAs with a height less than 1.2 m (48 in).

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Biographies

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Figure 1.
Toilet used for testing of mock-ups.

Figure 2.
Commercially available RA used for Part 1.

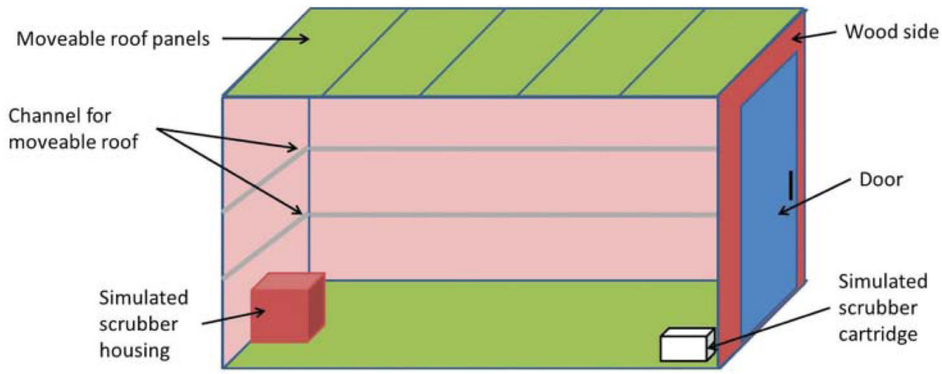

Figure 3.

Diagram of mock-up used for Part 2.

Note: Figure is not drawn to scale.

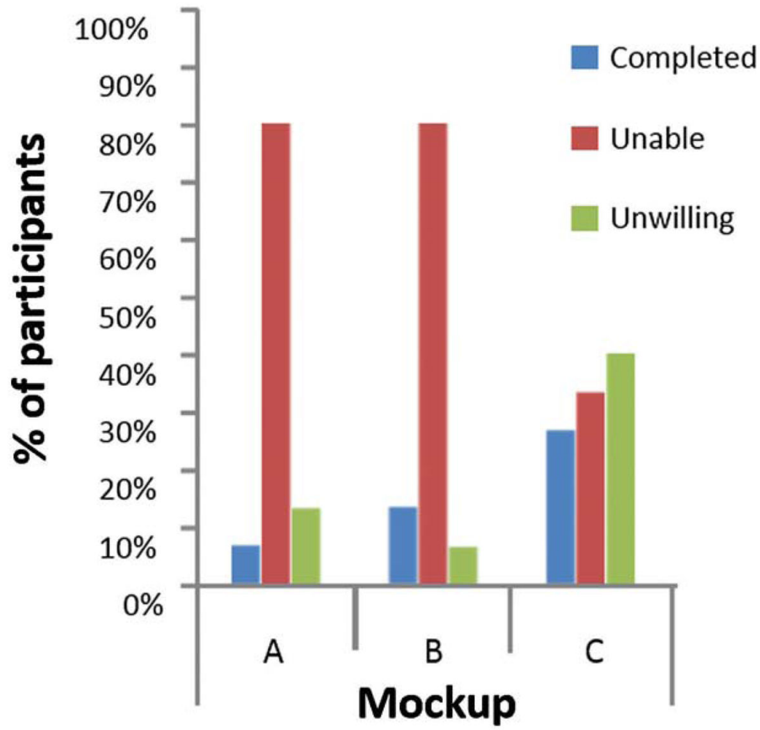

Figure 4.
Task completion rate for all participants (n = 15) for 'Set-up and simulated use of the toilet' at the 0.6 m (24 in) height for the three mock-ups tested.

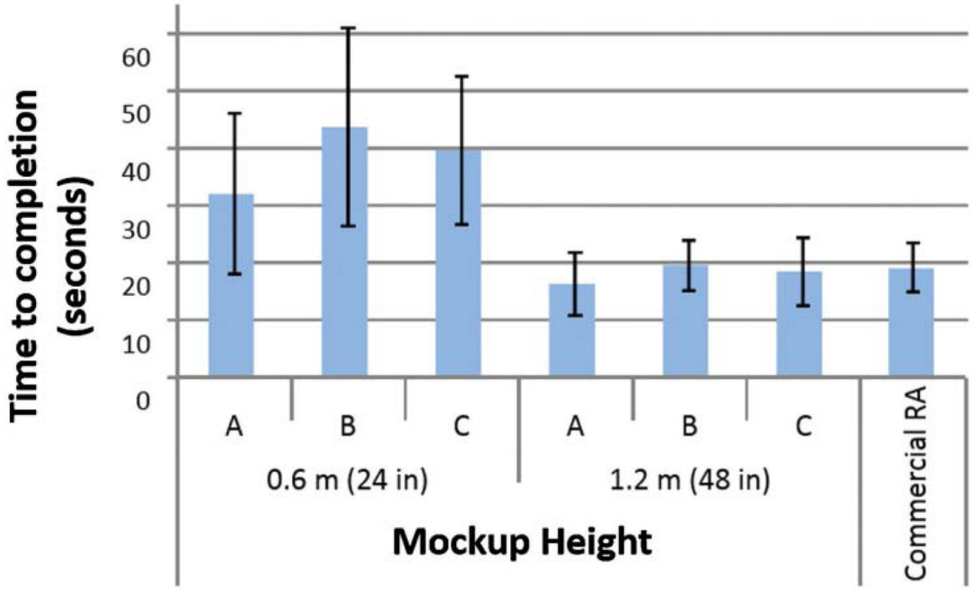

Figure 5.
Average (± STDEV) time to task completion for 'Changing of a CO_2 scrubber cartridge' for all participants ($n = 15$) for both the 0.6 m (24 in) and 1.2 m (48 in) heights and the commercially available RA.

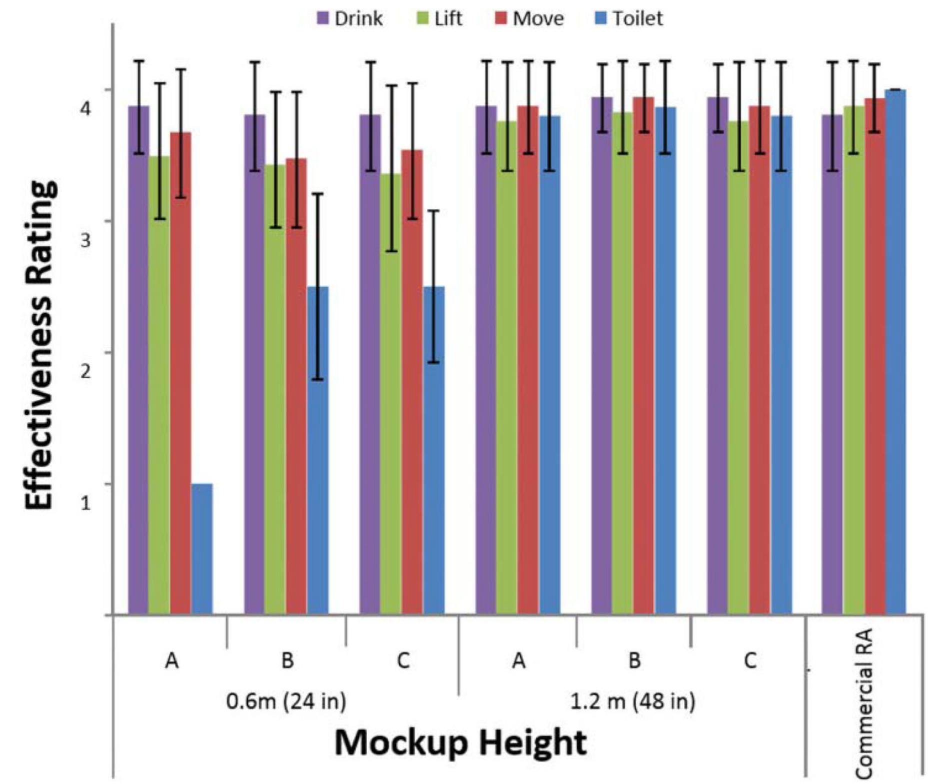

Figure 6.

Average (±STDEV) participant self-reported task effectiveness for all tasks for the participants who successfully completed the tasks ($n = 15$, except for Toilet A-24 $n = 1$, Toilet B-24 $n = 2$, Toilet C-24 $n = 4$) for both the 0.6 m (24 in) and 1.2 m (48 in) heights and the commercially available RA. (1) Totally Ineffective, (2) Ineffective, (3) Effective, (4) Totally Effective.

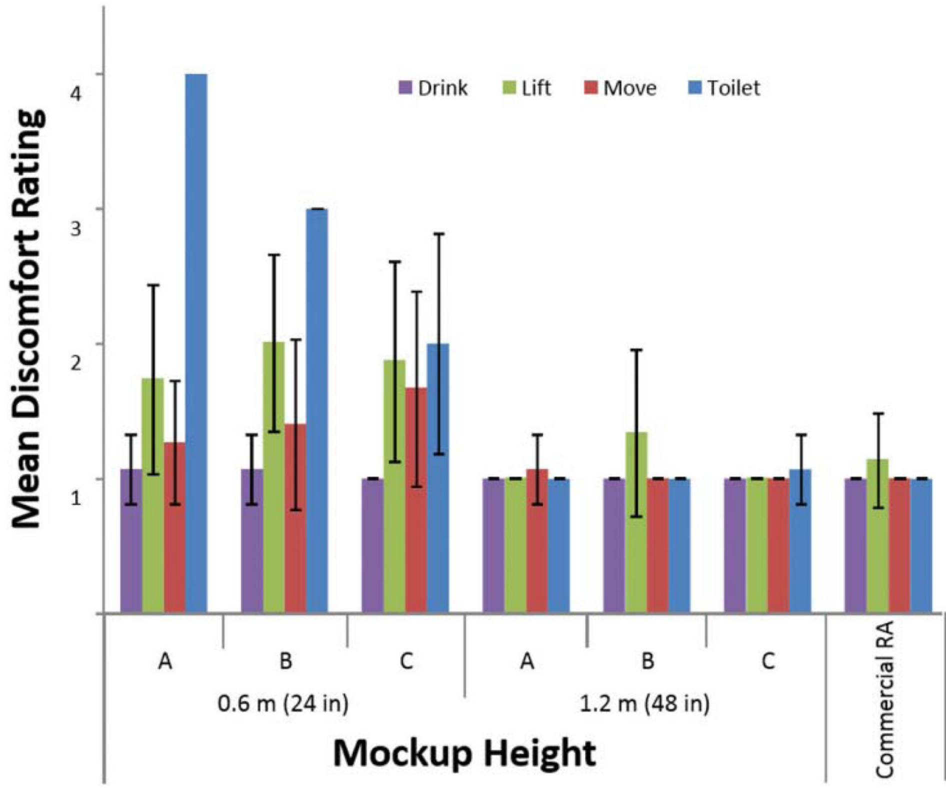

Figure 7.

Average (± STDEV) participant self-reported task discomfort for all tasks for the participants who successfully completed the tasks ($n = 15$, except for Toilet A-24 $n = 1$, Toilet B-24 $n = 2$, Toilet C-24 $n = 4$) for both the 0.6 m (24 in) and 1.2 m (48 in) heights and the commercially available RA. (1) No discomfort, (2) Mild discomfort, (3) Moderate discomfort, (4) Severe discomfort.

Figure 8.
0.6 m (24 in), 1.2 m (48 in), and 1.8 m (72 in) (left to right) mock-up heights for the move/carry portion of the ‘Changing of a CO_2 scrubber cartridge’ task.

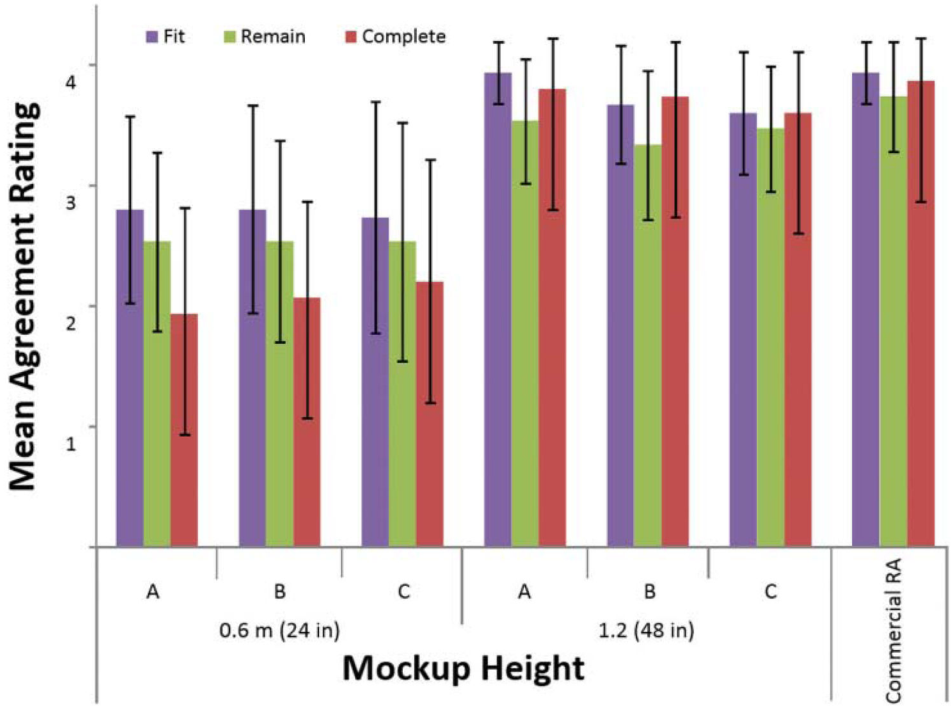

Figure 9.

Average (±STDEV) participant self-reported answers to general questions (n = 15) for both the 0.6 m (24 in) and 1.2 m (48 in) heights and the commercially available RA. (1) Strongly disagree, (2) Disagree, (3) Agree, (4) Strongly Agree.

Table 1

MSHA volume requirements.

Mining height (m (in))	Unrestricted volume (m^3 (ft^3)) per person*
0.9 (36) or less	0.85 (30)
>0.9 (36) to ≤1.1 (42)	1.06 (37.5)
>1.1 (42) to ≤1.2 (48)	1.27 (45)
>1.2 (48) to ≤1.4 (54)	1.5 (52.5)
>1.4 (54)	1.7 (60)

*Includes an adjustment of 0.3 m (1 ft) for clearances.

Table 2

Participants' anthropometric information.

Subject #	Age	Gender	Height (cm)	Weight (kg)	Hip breadth (cm)	Leg length (cm)
1	44	M	170	90	43	108
2	25	M	171	68	37	109
3	25	F	168	63	40	106
4	32	M	191	132	42	130
5	28	M	187	129	45	119
6	33	M	181	98	41	113
7	32	M	188	82	41	123
8	29	M	185	98	43	120
9	23	M	175	106	44	115
10	29	M	176	93	40	112
11	26	M	178	113	43	110
12	29	M	184	104	45	120
13	31	M	175	98	44	112
14	27	M	167	113	41	110
15	39	M	170	75	39	108